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Luis Varandas, Andrew Peach, Kevin Collins and Brian Nutter

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Poster paper

Design of a fast rotational chopper for X-ray pump–probe experiments at Diamond Light Source

LUIS VARANDAS†, ANDREW PEACH, KEVIN COLLINS AND BRIAN NUTTER

Diamond Light Source

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New trends in X-ray crystallography are concerned with the study of transient conditions of atomic structures, which take place after an energy activation agent is introduced. These time-resolved experiments require a fast mechanical shutter to interrupt the X-ray beam in a pump–probe cycle, with the aim to generate a stroboscopic effect. Thus, only diffraction data that are representative of the activated structure are actually collected. A rotating type of shutter, also known as chopper, is presented with the purpose to enable time-resolved experiments to be performed at I19 small-molecule single-crystal diffraction beamline. Exceptional stability in the rotational speed is critical to achieve the desired stroboscopic effect with minimum jitter. This requirement can be addressed only through design by the specification of suitable components and implementation of high-precision methods in manufacturing. The proposed equipment is comprised of a spindle supported on air bearings coupled to a slotted disc rotating inside a vacuum enclosure and driven by a brushless servo motor. Advanced control features are proposed to ensure that speed stability is achieved. Preliminary tests produced very encouraging results, giving strong indication that the chopper satisfies the specifications required for time-resolved experiments.

1. Introduction

Time resolution is one of the characteristics of pump–probe experiments and its quality of fundamental importance since the processes of interest take place usually in the sub-ms range. The specified delay between the pump and probe pulses must be accurate, ideally with no tolerances over the experiment cycle or, at least, with tolerances within the time resolution of the process in question.

The accuracy in the time elapsed between pump and probe is limited when fast shutters are used to create the probe pulses. Deviations introduced by the shutter mechanics affect these tolerances and can compromise the time resolution of the experiment if not duly addressed. From the chopper design perspective, these

† Email address for correspondence: luis.varandas@diamond.ac.uk

deviations may occur due to disturbances in rotational speed, presence of torque ripple or imperfections in manufacture.

Therefore, special consideration must be given to the specification of components, namely the type of bearings, motor/encoder set and control equipment. In addition, high-precision methods in the production of the mechanical parts are required.

2. Project requirements

The nature of the pump–probe experiments to be carried out on I19 beamline will require pulse frequencies ranging from 10 Hz to 10 kHz. With this in mind, a high-repetition-rate type of chopper is preferred, similar to the designs described by Gembicky *et al.* (2005) and Fullagar *et al.* (2000), i.e. of rotation axis parallel to the X-ray beam and with interchangeable discs.

A number of discs with different slot configurations are proposed by Varandas (2009) to enable the equipment generate those frequencies. However, for initial tests and operation the chopper is supplied with a single disc containing 20 identical slots of 0.335 mm aperture each. Given the design, speeds range from 300 to 30,000 rpm; this particular configuration suits experiments with lifetimes from 100 up to 1 μs.

Such time scales require exceptional angular speed stability. Any disturbances introduced by the mechanics must be well below the μs range. For this project, it is intended to keep these disturbances to the angular speed or jitter, within 5% of a μs.

3. Chopper design characteristics

In order to ensure that this requirement is achieved, the design process was focused on the selection of components that can afford smooth speed operation at any selected speed within the range from 300 to 30,000 rpm. This imposed restrictions that reduced considerably the number of suitable options.

A non-contact type of bearing was sought to avoid torque ripple issues caused by friction and/or changes in the properties of the oil lubricant. An aerostatic air bearing was eventually specified since it satisfies the technical criteria at a more attractive cost than the magnetic alternative and has previous examples of successful use in similar equipment (Fullagar *et al.* 2000; Gembicky *et al.* 2005). The design, developed by Fluid Film Devices Ltd, consists of two journal bearings of different diameters machined to a stainless-steel shaft, resulting in a tapered single spindle piece of 193 mm in length. Nominal bearing clearance is 11 μm which required high-precision machining process during manufacture and tight balancing tolerances.

The disc is a 155 mm diameter stainless-steel unit which is coupled to the larger diameter end of the spindle (figures 1 and 2). To reduce the overall load and losses, the disc is enclosed within a vacuum chamber which creates a requirement to specify appropriate means of sealing at the point where the shaft enters the vacuum space. A method that employs fine machining clearances between the spindle and casing combined with differential vacuum pumping known as capillary sealing was adopted. This technique complements the air bearing arrangement since it is able to sustain a reasonable vacuum level in the chamber without the need of a physical seal; hence there is no contact to the rotating shaft. Note that hermetic vacuum is not achieved though.

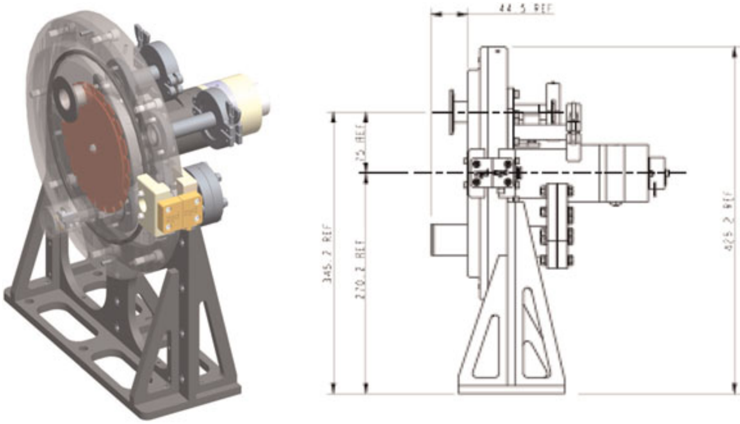

FIGURE 1. Chopper general assembly.

The brushless servo DC motor of frameless construction allows direct assembly to the spindle. This aims to eliminate issues related to mechanical couplings such as backlash and vibration and to minimize the total inertia of the shaft mechanism. Additional characteristics were also specified in the motor design to reduce the effects of torque ripple originated by the interaction between the stator slots and the permanent magnets in the rotor (cogging or detent torque).

4. Evaluation tests and concluding remarks

A specific control technique known as phase-locked loop is proposed to provide precise speed control of the motor and this is implemented by using an external

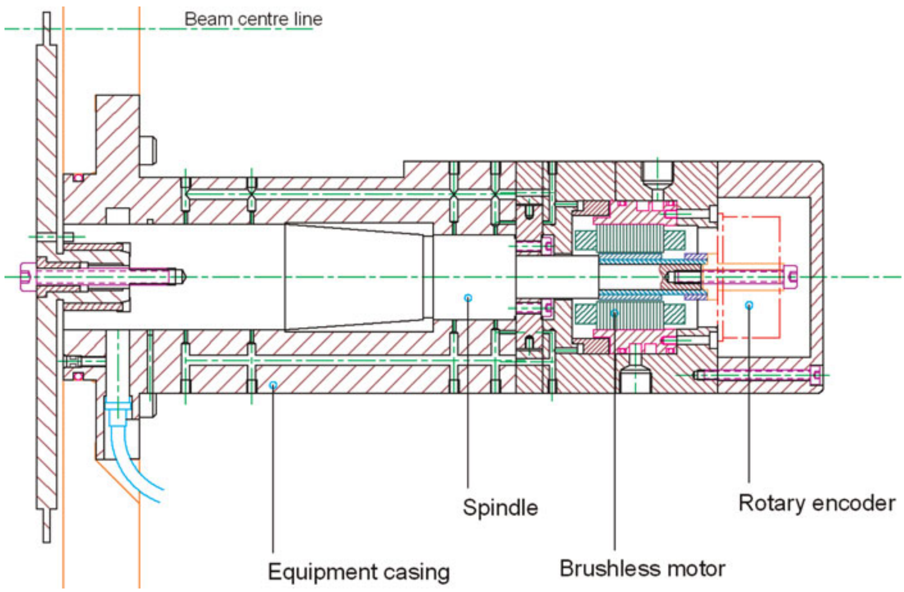

FIGURE 2. Cross-sectional view of the chopper and its key components.

pulse signal of stable and accurate frequency as the reference for the controller. Consequently, further refinement in the tuning of the Proportional-Integral-Derivative (PID) loop is required to ensure maximum reduction of the following error.

A series of preliminary tests were then done to evaluate the quality of the mechanical design and the tuning of the controller. Results from mechanical tests (Varandas 2009) registered a maximum orbit diameter of 4.91 μm at 30,000 rpm for a bearing clearance diameter of 22.5 μm, which demonstrates the high-level balancing of the equipment. The vacuum level achieved in the disc chamber is in the range of 3×10^{-2} mbar, which is quite satisfactory for the objectives of the project and confirms the suitability of the capillary sealing arrangement.

In the tuning procedure it became clear that the measures to reduce friction losses made the system inherently under-damped. Nonetheless, this does not represent a problem according to the operational criteria and considering the inertial forces involved. Steady-state performance evaluated at different speeds registered the following error of just one encoder count, indicating that fine speed stability is feasible.

At the present stage, these results are the best available evidence to assess the equipment performance. Further work is yet to be done in order to assess whether the system satisfies the requirements of time-resolved experiments in terms of jitter, as part of a complete pump–probe experimental set-up. Nevertheless, these results are very satisfactory and encouraging, suggesting that the design achieved the specified objectives. This provides strong reassurance about the chances of project success.

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